ISSUES RELATING TO THE USE OF ARC HEATERS FOR DIRECT-CONNECT SCRAMJET TESTING*

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ABSTRACT

Issues relating to the use of arc-heated air for scramjet direct-connect testing are discussed. Direct-connect simulation issues are reviewed. The ability to satisfy simulation requirements is addressed. The effect of NO and copper contamination is discussed, as well as spatial and temporal flow fluctuations. It is concluded that arc heaters can provide a useful test environment in the simulated Mach number range, M_{sim} = 6-10.

INTRODUCTION

Electric arc heaters have been used for over 30 years to generate pressures and enthalpies characteristic of reentry flight for testing and evaluation of thermal protection materials. Issues of flow quality and uniformity are of secondary importance for materials testing. However, over the years there has been an ongoing effort to better characterize arc-heated flows. The purpose of this paper is to review what is known about these flows and assess their applicability to direct-connect scramjet testing. Arc heaters have a potential role to play, especially in the simulation Mach number range, M_{sim} = 6-10. Indeed the AHSTF (Arc Heated Scramjet Test Facility) at LaRC has already played a very significant role in the Hyper-X 'engine flowpath development' test program[1] at M_{sim} = 7. The role of arc heaters in hypersonic testing has been treated by a number of authors; [2-4] arc heaters have at best received mixed reviews concerning the role they might play in scramjet testing. The simulation issues involved will be reviewed, as well as issues of flow contamination with nitric oxides or copper and spatial and temporal flow uniformity.

SIMULATION ISSUES

There is a hierarchy of simulation requirements to be considered when setting up a direct-connect scramjet test. The total enthalpy is generally considered a mandatory parameter to match. The total pressure and the combustor static pressure would be considered next. A minimum level of static pressure is required in order for combustion to be sustained. In order to relate the various parameters at the combustor entrance, the inlet design must be known. In the example shown in Fig. 1, a "Billig" inlet operating at a free-stream q of 1000 psf was assumed. The resulting parameters at the combustor entrance are shown in Fig. 1 as a function of simulated flight Mach number. If the total pressure can be dupli-

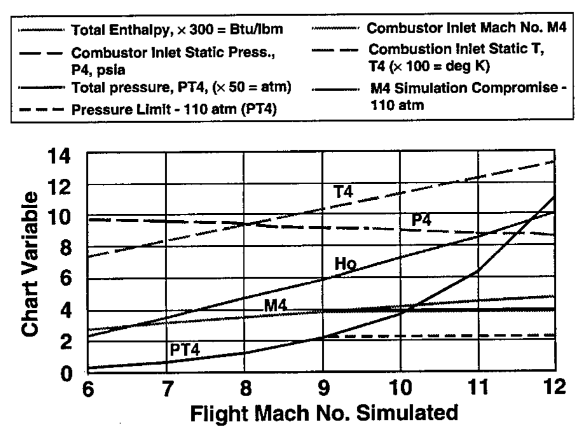

Fig. 1. Scamjet direct-connect billig inlet, q = 1000 psf.

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cated and an appropriate nozzle is used to replicate the Mach number, then the static conditions will be matched. If, however, the total pressure cannot be achieved, the simulation is compromised. This is usually done as follows: the nozzle Mach number is selected such that the static pressure at the combustor is matched correctly. This implies some mismatch in the static temperature as well as the Mach number.

The current practical limit for arc heater operation is 100 atm. Arc heaters have been operated as high as 200 atm, but segmented arc heaters have not been operated reliably at pressure levels significantly above 100 atm. This limit is depicted in Fig. 1, as well as the necessary Mach number variation required to maintain the appropriate static pressure. The H3 arc heater at AEDC can provide a 100 atm and 3000 Btu/lbm test condition at a scale that will allow testing a near full-size missile application scramjet in direct-connect mode. The operating map for the H3 heater was presented in Ref. 5.

NITRIC OXIDES IN THE FLOW

A frequently mentioned issue relating to testing with arc heaters is the presence of NO in the test gas. There are a number of misconceptions relating to this subject. The following discussion is intended to reinforce the fact that the chemical changes in arc-heated air are equivalent to those in any other device which expands heated air from a given stagnation reservoir state. At pressures in the 100-atm range, the arc heater chamber will always be in chemical equilibrium. An equilibrium concentration plot for NO is shown in Fig. 2. Peak concentrations occur in the 4500-5000 K range. Coincidently, typical stable arc heater operating points are also in this range, as shown by the two points labeled for the AEDC and Langley heaters. At actual 'arc' temperatures (~10,000 K), everything tends to dissociate, including NO. The total enthalpies corresponding to Mach 8 and 12 simulation are labeled to orient the reader. At all simulation Mach numbers lower than 12, cold air dilution will be required to match the enthalpy.

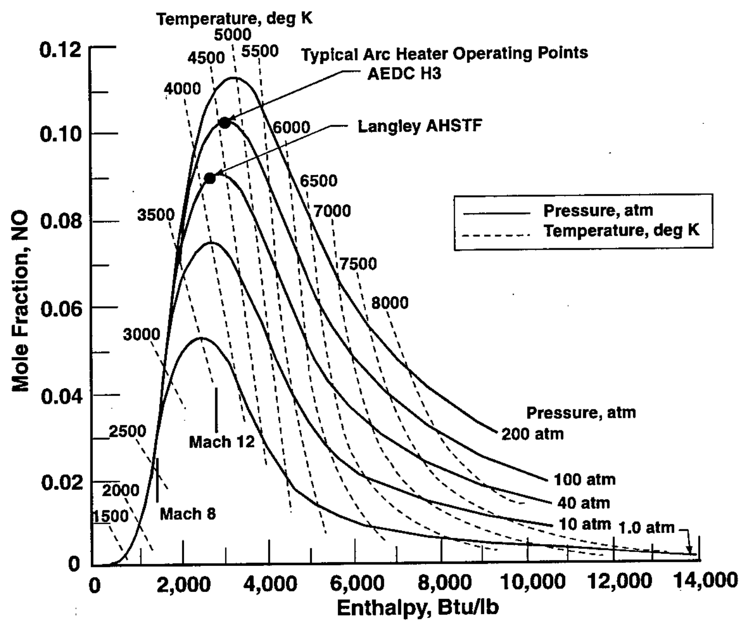


Fig. 2. Nitirc oxide in high-temperature equilibrium air (NO) mole fraction vs. enthalpy at constant pressure.

RESERVOIR CHEMISTRY

The reservoir (between the arc chamber and the nozzle) will be in chemical equilibrium except at the low end of the simulation Mach number range, i.e. M_{sim} = 6 and 7. A typical stable arc heater operating condition would have a stagnation enthalpy corresponding to Mach 12 simulation; hence, it is necessary to dilute with cold air in the reservoir in order to achieve the correct enthalpy. At M_{sim} = 6 or 7, dilution can cause the reservoir temperature to drop so severely that the chemistry becomes so slow that the flow does not have time to equilibrate while in the reservoir. The exact behavior is dependent on the mixing chamber design. The NO concentration data shown in Fig. 3 for M_{sim} = 6 and 7 are consistent with dilution only and are greater than the chemical equilibrium values. The data shown are from the LaRC AHSTF, and a comprehensive explanation of what happens can be found in Ref. 6. At M_{sim} = 8 it can be seen that the reservoir has achieved chemical equilibrium; however, the flow freezes very quickly in the nozzle expansion. A

better feeling for how the pressure affects the time required to attain reservoir equilibrium can be obtained from the computational results shown in Fig. 4. A supraequilibrium NO concentration of 15 percent was imposed, and the time to equilibrium was computed. A characteristic distance was computed using a velocity typical of flow inside an arc heater. It is seen that a flow distance of only 0.01 in. is required to reach equilibrium at 100 atm and 4000 K.

NOZZLE CHEMISTRY

As noted above, the NO concentration freezes very early in the nozzle expansion for M_{sim} = 8. For reference, equilibrium curves are shown in Fig. 3 for the reservoir and for the nozzle exit as a function of M_{sim}. As the temperature increases for the larger simulation Mach numbers, freezing is delayed, the NO concentration peaks under 5 percent, and then gradually decreases, tending toward the nozzle exit equilibrium value at M_{sim} = 12. The nozzle scale was what would be required for an AEDC H3 arc heater application, i.e., a nozzle some 2 ft long. The predicted effect of NO on ignition time for H_2/air is shown in Fig. 5. The NASA calculations and the AEDC calculations were done with the same code but with a slightly different reaction set. The Argonne calculation was done as a check with a different code. The calculations at a combustion static temperature of 900 K are typical of M_{sim} ~ 7, 1250 K typical of M_{sim} = 9-10, and 2000^+ K typical of M_{sim} = 15^+. It is noted that for temperatures characteristic of M_{sim} = 9 or 10, there is no appreciable effect. The effect of NO on thrust was evaluated in Ref. 6 for concentrations up to 3 percent by mole. At 3 percent, the thrust was enhanced from 1 to 4 percent, depending on the fuel equivalence ratio.

FLOW UNIFORMITY

One of the major uses of arc heaters has been to simulate reentry environments. For this application, maximum pressure and heating rates were a common objective. The Mach number was kept in the low supersonic regime in order to maximize pressure, and the nozzles were short-coupled with the heater to minimize thermal losses. The impact pressure was relatively uniform, as shown in Fig. 6a, but the enthalpy profile is somewhat parabolic with the maximum value at the centerline (see Fig. 6b), reflecting the centrally located heat release in the arc heater itself. The enthalpy shown is inferred from measured heat-trans-

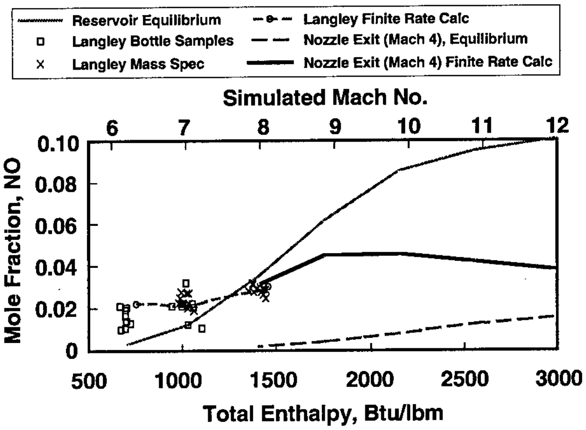


Fig. 3. Nitric oxide levels, Scramjet direct-connect scale: H3 arc heater, 100 atm.

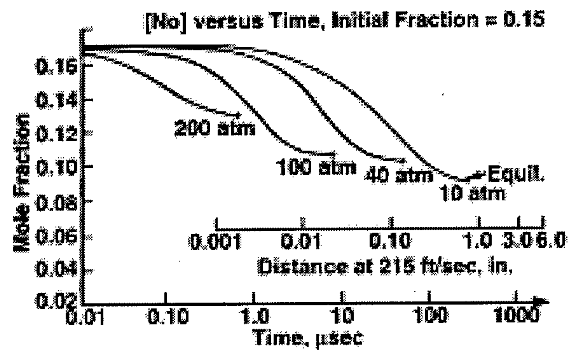


Fig. 4. Nitric oxide relaxation from supraequilibrium 0.15 mole fraction, P = 10 atm, T = 4000 K, P = 300 atm, T = 5000 K.

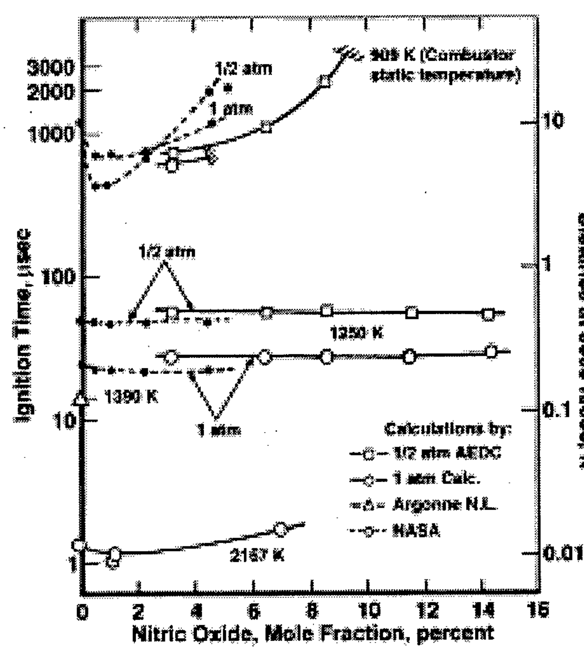
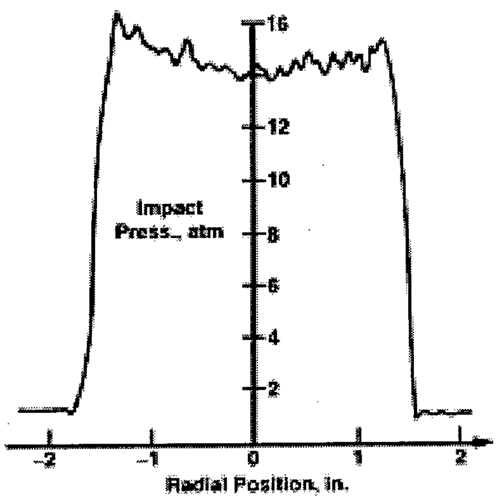


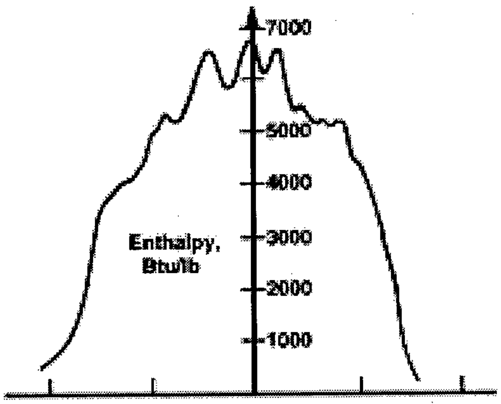
Fig. 5. Effect of nitric oxide on ignition time, stoichiometric H_2/air.

fer rates and impact pressure by using the Fay and Riddell heat-transfer relation. If maximum heating rate at the stagnation point is desired, the type of profile shown in Fig. 6b would be desirable.

Other types of testing require a more uniform flow. A large stilling chamber has been used between the arc heater and the nozzle in order to improve the flow uniformity. Cold air has also been injected in order to reduce the flow enthalpy level. Typical impact pressure and enthalpy profiles are shown in Figs. 7a-b. There is a marked improvement in the uniformity of the enthalpy profile and a smaller improvement in the impact pressure profile. The effect of the stilling chamber on the spatial and temporal fluctuations in the flow is summarized in Table I. There is a notable improvement in the spatial uniformity but temporal fluctuations are not diminished, remaining in the range of 3 to 4 percent in pressure and 8 to 10 percent in enthalpy. Some applications require a flow enthalpy lower than can be achieved in the arc heater because of stability requirements. The mixing chamber has also been successfully used to lower the flow enthalpy through injection of cold air. The thermal losses of the chamber itself lower the enthalpy some 7-10 percent. The effect of cold air injection on fluctuations is small, as shown in Table I.

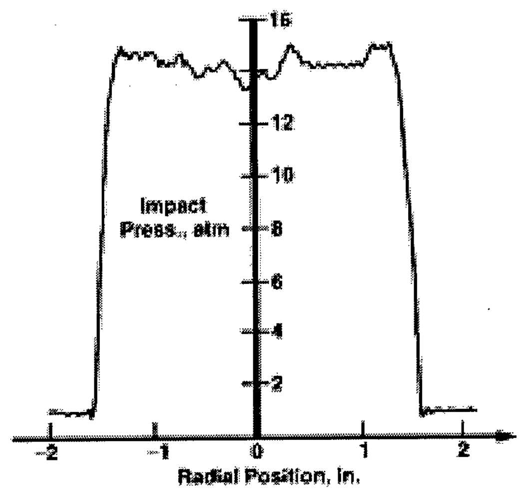


a. Pressure

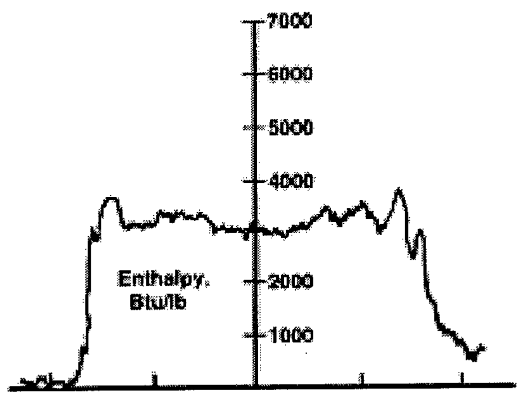


b. Enthalpy

Fig. 6. Enthalpy and pressure profiles, standard reservoir, P_0 = 105 atm, H_0 = 2850 Btu/lb.



a. Pressure



b. Enthalpy

Fig. 7. Enthalpy and pressure profiles, large stilling chamber, P_0 = 114 atm, H_0 = 2650 Btu/lb.

Table I. Effect of Large Stilling Chamber and Cold Air Mixing on HEAT-H1 Flow Quality

Configuration		Profile Shape, Edge-to-℄ Ratio		Temporal Fluctuation Level		℄-to-Bulk Enthalpy Ratio
Reservoir	Cold Air	Pressure	Enthalphy	Pressur, percent	Enthalpy, percent	
Standard	None	1.08	0.52	± 3.2	± 10.4	2.25
Large		1.05	1.06	± 3.8	± 7.8	1.16
Standard	36 percent	1.06	0.99	± 4.8	± 11.1	1.48
Large	70 percent	1.06	1.09	± 7.2	± 10.1	1.13

COPPER CONTAMINATION

Some copper is lost from the electrodes. The total loss has been measured.[7] If it is assumed that all of the Cu gets into the flow, which it probably does not, an upper limit on the amount of Cu in the H1 segmented arc heater flow is 90 ppm by mole, or 200 ppm by mass. It was shown in Ref. 8 that the Cu in the flow will remain mostly in atomic form, with only small amounts of CuO, CuH, and CuOH, and will not condense in any appreciable amount until the temperature is significantly below 1000 K. The copper will generally not participate in combustion reactions. However, ANL[8] has investigated the possibility of Cu catalyzing the recombination of free radicals and the effect it would have on H2 combustion. The results of a possible scenario are shown in Fig. 8. No effect is seen on the ignition time. A 10-percent reduction in the total reaction time is noted for the 90-ppm level measured in H1.

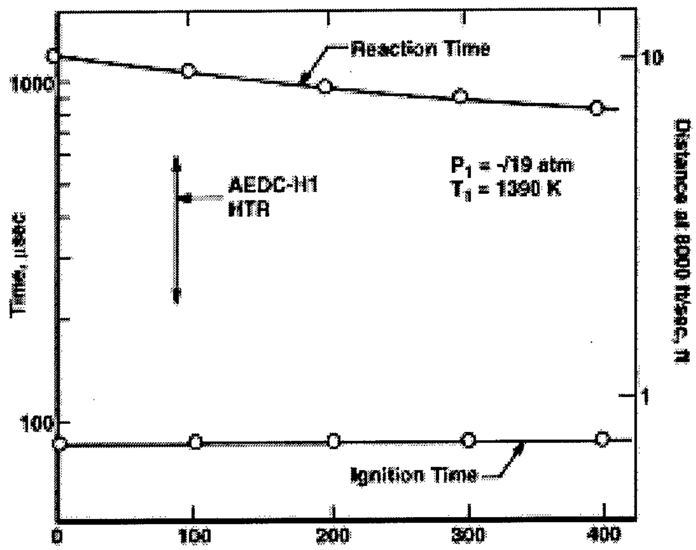


Fig. 8. Effect of copper catalyst on stoichiometric combustion of H_2/air.

CONCLUSIONS

It has been shown that arc heaters can be a useful tool for scramjet direct-connect testing in the M_{sim} = 6-10 range. The total enthalpy can be easily duplicated in this range. The total pressure can be duplicated up to M_{sim} = 9 with the current state-of-the-art 100-atm operation. Some simulation compromise would be required at M_{sim} = 10. A reasonable arc heater development goal, heater operation at 200 atm, would allow total pressure duplication at M_{sim} = 10. Nitric oxide in the test flow would reach a maximum value of 5 percent by mole. The effect on ignition time is small, and a correction can be made for the effect on thrust. It has been shown that copper will have a very minor catalytic effect on the combustion process. Spatial flow nonuniformity can be mitigated with a stilling chamber. Temporal fluctuations are relatively large (4 percent in pressure, 10 percent in enthalpy).

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